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A Final Report on

THREE-DIMENSIONAL STRUCTURE OF TRANSITIONAL BOUNDARY LAYERS

CONTRACT NUMBER AFOSR-F49620-85-C-0089

From

Air Force Office of Scientific Research
Bolling Air Force Base
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September 1990

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ABSTRACT

The final report for Contract AFOSR-F49620-85-C-0089 is given. Detailed experiments were performed of boundary layers undergoing instabilities and transition to turbulence. The experiments utilized multiple hot-wire anemometer techniques in combination with recently developed flow visualization and computational techniques. The use of phase-correlated and conditionally-sampled measurements permitted the study of the origin and evolution of the characteristic large-scale structures of transitional boundary layers. Fundamental transition mechanisms, the control of random background disturbances, and the receptivity of the boundary layer to external disturbances that lead to transition were studied.

This work represents the most detailed study of sound and turbulence receptivity mechanisms that lead to transition in boundary layers in both natural and controlled situations. It lays the foundation for more advanced work in boundary-layer transition and control with sound and 3-D roughness.

TABLE OF CONTENTS

1. INTRODUCTION

The origins of turbulent flow and the transition from laminar to turbulent flow are the most important unsolved problems of fluid mechanics and aerodynamics. There are any number of applications for information regarding transition location and the details of the subsequent turbulent flow. A few examples can be given here. (1) Nose cone and heat shield requirements on reentry vehicles and the "aerospace airplane" are critical functions of transition altitude. (2) Vehicle dynamics and "observables" are modulated by the occurrence of laminar-turbulent transition. (3) Should transition be delayed with Laminar Flow Control on the wings of large military aircraft, a 25% savings in fuel will result. (4) Lack of a reliable transition prediction scheme hampers efforts to accurately predict airfoil surface heat transfer and to cool the blades and vanes in gas turbine engines. (5) The performance and detection of submarines and torpedoes are significantly influenced by turbulent boundary-layer flows and efforts directed toward drag reduction require the details of the turbulent processes. (6) Separation and stall on low-Reynolds-number airfoils strongly depends on whether the boundary layer is laminar, transitional, or turbulent.

The common thread connecting each of these applications is the fact that they all deal with *bounded shear flows* (boundary layers) in *open systems* (with different upstream or initial amplitude conditions). It is well known that the stability, transition, and turbulent characteristics of bounded shear layers are fundamentally different from those of free shear layers. Likewise, the stability, transition, and turbulent characteristics of open systems are fundamentally different from those of closed systems. The distinctions are vital.

At the present time no mathematical model exists that can predict the transition Reynolds number on a flat plate. One obvious reason for this lack is the variety of influences such as indigenous disturbances, freestream turbulence, surface geometry and roughness, sound, heat transfer, ablation, etc. which are incompletely understood, yet may trigger transition through a forced response of the flow as a nonlinear oscillator. A second reason, of course, is the poor understanding of the free response of this nonlinear oscillator, i.e. of the fundamental mechanisms which lead initially small disturbances to transition.

The recent progress in this area, summarized by Saric (§ 2.1.7) is encouraging, in that three distinct transition mechanisms have been found experimentally. The theoretical work successfully identifies the operative mechanism in each case and finds them to be amplitude and Reynolds-number dependent. At last the possibility exists for developing a transition criterion based on more rational ideas than the e^9 method. However, the theory remains rather incomplete.

The major needs in the transition area are (1) to extend the catalogue of relevant mechanisms and to develop deeper understanding of their physics, (2) to model, in more detail, the breakdown process itself, (3) to understand how freestream disturbances are entrained into the boundary layer, i.e. to answer the question of receptivity, and (4) develop techniques for the control of disturbances that lead to transition. The four problem areas are intimately related in that amplitude and spectral characteristics of the disturbances inside the laminar viscous layer strongly influence which type of transition occurs.

The research supported by this contract addressed the last two topics: *receptivity* and *control*. In Section 2, the accomplishments are listed for the period of the contract. In Section 3, the technical highlights are described with reference to the different publications.

2. ACCOMPLISHMENTS

The accomplishments during the period of the contract are listed below in skeletal form in the order of *Publications, Students, Presentations, and Facilities.*

2.1. Publications

1. "Boundary-Layer Transition: T-S Waves and Crossflow Mechanisms," W.S. Saric, Proc. *AGARD Special Course on Aircraft Drag Prediction and Reduction*, VKI, Belgium, AGARD Report No. 723, May 1985.

2. "Visualization of Different Transition Mechanisms," W.S. Saric, *Phys. Fluids, Vol. 29, No. 9*, 1986, p. 2770.

3. "Boundary Layer Transition to Turbulence: The last five years," W.S. Saric, *Proc. 10th Symposium on Turbulence*, Rolla, September 1986.

4. "Fundamental Requirements for Freestream Turbulence Measurements," W.S. Saric, S. Takagi, and M.C. Mousseux, *AIAA Paper No. 88-0053,* January 1988.

5. "Control of Random Disturbances in a Boundary Layer," P.T. Pupator and W.S. Saric, *AIAA Paper No. 89-1007*, March, 1989.

6. "The ASU Unsteady Wind Tunnel" W.S. Saric, *ASU CEAS Tech. Rpt. CR-R 89030*, April 1989.

7. "Boundary-Layer Stability and Transition," *Proc. 5th International Conf. on Numerical Ship Hydrodynamics*, Hiroshima, Japan, September 1989.

8. "Comparison of Local and Marching Analyses of Görtler Instability," H.L. Day, T. Herbert, and W.S. Saric, *AIAA J., Vol. 28, No. 9,* 1990.

9. "Boundary-Layer Receptivity: Part 1. Freestream Sound and 2-D Roughness Strips," W.S. Saric, J.A. Hoos, and Y. Kohama, *ASU CEAS Tech. Rpt. CR-R-90191*, May 1990.

2.2. Students Supervised

Ph.D. Students

1. R. H. Radetzsky, "Boundary-Layer Receptivity of Three-Dimensional Roughness Elements in the Presence of Sound", expected Spring 1992.

M.S. Students

2. M. C. Mousseux, "Flow Quality Improvements in the Arizona State University Unsteady Wind Tunnel," August 1988.

3. P. T. Pupator, "Control of Random Two-Dimensional Disturbances in a Boundary Layer," December 1988.

4. J. A. Hoos, "Boundary Layer Receptivity Experiments on a Flat Plate," May 1990.

Senior Projects

5. B. Yonkovich, "Wind Tunnel Test-Section Design," May 1987.

6. C. Kaus, "3-D Traverse Design," December, 1987.

7. T. Hendricks and P. Simonich, "Design of a Turning Vane Heat Exchanger," May 1989.

8. M. Gersten, "Design of Special Optics for a Laser-Doppler Anemometer," August 1989.

2.3. Invited Talks and Lectures

1. "Subharmonic Route to Turbulence in Boundary Layers," (a) GALCIT, Caltech, February 1985. (b) Princeton University, February 11, 1986.

2. "Stability and Transition in Bounded Shear Flows," *(Invited)* Texas A&M University, November 1, 1985.

3. "The Görtler Instability," *(Invited)* AIAA Professional Study Series on Instabilities and Transition to Turbulence, Cincinnati, July 13-14, 1985.

4. "Boundary-Layer Transition: T-S Waves and Crossflow Mechanisms," *(Invited) AGARD Special Course on Aircraft Drag Prediction and Reduction*, VKI, Brussels, May 20-24, 1985 and NASA Langley, August 19-21, 1985; AGARD Report No. 723.

5. "Linear Stability: The Görtler and Other Nonparallel Problems," (Invited) International Workshop on Stability and Transition in Bounded Shear Flows, Tucson, Arizona, November 22-23, 1985.

6. "Initiating Chaos in Boundary Layers," *(Invited)* Chaotic Motion in Open Flows Workshop, UC Nonlinear Studies, Lake Arrowhead, California,

February 7-9, 1986.

7. "Is Chaos Relevant to Shear Flows," Panelist: Chaotic Motion in Open Flows Workshop, UC Nonlinear Studies, Lake Arrowhead, California, February 7-9, 1986.

8. "ASU Unsteady Wind Tunnel," (a) AIAA 14th Aerodynamic Testing Conf. West Palm Beach, March 5-7, 1986, AIAA Paper No. 84-0588, (b) 2nd Annual Arizona Fluid Mechanics Meeting, Tempe, April 4-5, 1986.

9. "Stability of Three-Dimensional Boundary Layers: Theory and Experiment," *(Special Lecture)* 3rd Asian Congress of Fluid Mechanics, Tokyo, Japan, September 1-5, 1986.

10. "Transition to Turbulence in Boundary Layers: The Last Five Years," *(Invited Lecture)* (a) 10th Symp. on Turbulence, Univ. Missouri, September 22-24, 1986; (b) NASA-Ames Research Center, March 13, 1987; (c) University of Cincinnati, April 10, 1987, (d) ONERA, Toulouse France, May 18, 1987, (e) Institute de Mecanique des Fluids, Marseille France, May 21, 1987; (f) Univ Minnesota, February 2, 1988; (g) National Aerospace Laboratory, Tokyo, April 8, 1988, (h) Hokkaido Univ., Sapporo, Japan, April 13, 1988, (i) Univ. of Western Ontario, London, Canada, November 23, 1988.

11. "Experiments on Boundary-Layer Transition," *(Invited)*, ICASE-NASA Langley Workshop on Stability and Transition, November 21, 1986.

12. "Stability of Hypersonic Attachment-Line Flows," *(Invited)*, ICASE-NASA Langley Workshop on Stability and Transition of High Mach Number Shear Layers, March 20, 1987.

13. "Three-Dimensional Stability of Boundary Layers," *(Invited)*, Symposium on Perspectives in Turbulence, Göttingen, F.R.G., May 11-15, 1987.

14. "Experiments on Unsteady Separation and Stall," ASME Applied Mechanics, Bioengineering and Fluids Engineering Conference, June 14-17, 1987.

15. "The ASU Unsteady Wind Tunnel and Fundamental Requirements for Freestream Turbulence Measurements" AIAA Aerospace Sciences Meeting, Reno, January 12-16, 1988, AIAA Paper No. 88-0053.

16. "On the Görtler Instability of Flows with Periodic Curvature," *(Invited)*, (a) Symposium in honor of Itiro Tani, Tokyo, April 9, 1988; (b) Tohoku Univ., Sendai, Japan, April 11; (c) Az Fluid Mech. Conference, April 30, 1988; (d) 41st Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Buffalo, New York, November 1988, Bull. Amer. Phys. Soc. 33, 2283; (e) ICASE/NASA Langley Research Center Workshop on Instability and Transition, May 16, 1989.

17. "Stability and Transition in Three-Dimensional Boundary Layers," ***(Invited)***, AGARD Symposium on Fluid Dynamics of Three-Dimensional Turbulent Flows and Transition, Cesme, Turkey, October 3-6, 1988.

18. "Secondary Instabilities Leading to Transition," ***(Invited)***, E.R.C.O.F.T.A.C., Course on Physics of Transition from Laminar to Turbulent Flow, Politecnico di Torino, Torino, Italy, October 13, 1988.

19. "Three-Dimensional Transition," ***(Invited)***, E.R.C.O.F.T.A.C., Course on Physics of Transition from Laminar to Turbulent Flow, Politecnico di Torino, Torino, Italy, October 14, 1988.

20. "Control of Random Disturbances in a Boundary Layer," (a) 2nd AIAA Shear Flow Control Conference, Tempe, AZ, March 13-16, 1989, AIAA Paper No. 89-1007; (b) 4th Arizona Fluid Mechanics Conference, February 1989.

21. "Sources of Error in Low-Speed Stability Experiments," ***(Invited)***, ICASE/NASA Langley Research Center Workshop on Instability and Transition, June 1, 1989.

22. "Boundary-Layer Stability and Transition," ***(Invited Keynote Lecture)***, Fifth International Conference on Numerical Ship Hydrodynamics, Hiroshima, Japan, September 25-28, 1989.

23. "Boundary-Layer Receptivity to Freestream Turbulence and Sound," (a) 42nd Annual Meeting of the Division of Fluid Dynamics of the American Physical Society, November 19-21, 1989, Bull. Amer. Phys. Soc. 34, p. 2260. (b) ***(Invited)*** International Congress of Fluid Mechanics, Cairo, Egypt, January 2-4, 1990., (c) 6th Annual Arizona Fluid Mechanics Meeting, Tempe, Feb 4-5, 1990

2.4. ASU Unsteady Wind Tunnel

The ASU Unsteady Wind Tunnel is a major research facility that was established at ASU by W. S. Saric during the period of this contract. This effort involved the acquisition and transport of key elements from the Klebanoff-designed unsteady tunnel at the National Bureau of Standards, building construction at ASU, redesign and construction of 75% of the tunnel, purchase of supplies, tools, and instrumentation, and the accounting and subcontracting as well as the supervision of staff and student workers. The building was completed June 1985 and the tunnel became operational December 1987 with total expenditures of over $1,000,000 from University, Federal Agency, and Local Industry support (see Saric, § 2.1.6).

3. TECHNICAL HIGHLIGHTS

3.1. ASU Unsteady Wind Tunnel

The establishment of this national resource was possible in part by the support from this contract. Publications 2.1.*4* and 2.1.*6* and M.S. Thesis 2.2.*2* detail the flow quality of the remarkable facility and it is not necessary to list all of the details. The flow uniformity meets the highest standards and the turbulence levels are low enough to conduct sensitive receptivity experiments. The data-acquisition system makes it possible to conduct experiments that were not possible 10 years ago.

3.2. Control of Random Disturbances in the Boundary Layer.

This experiment successfully demonstrated the ability to cancel *random* 2-D disturbances within the boundary layer. The details are given in Publication 2.1.*5* and the M.S. Thesis 2.2.*3*.

Previous control and cancellation experiments were limited to a single-frequency wave-superposition technique where the initial input signal was used as part of the control logic. Attempts by these authors to cancel random disturbances were unsuccessful. As a first step in controlling the random *3-D* disturbances within a boundary layer, the logical first attempt was to try the cancellation of 2-D disturbances. Since the harbingers of transition are 2-D T-S waves from upstream disturbances, the elimination of these waves should delay transition.

By developing special signal processing and feed-back techniques (described in the paper), we were able to reduce by an order of magnitude the spectrum of random disturbances and hence delay transition from $Re_x \approx 3.5 \times 10^6$ to $Re_x \approx 5.0 \times 10^6$. These techniques can now be extended to the control of 3-D disturbances.

3.3. Boundary-Layer Receptivity: Freestream Sound and 2-D Roughness Strips

The response of the forced oscillations of a Blasius boundary layer over a flat-plate model caused by an acoustical disturbance was investigated for frequencies of 70 Hz - 85 Hz. The most important aspect of this experiment was to determine and accurately document both the disturbance in the boundary layer caused by the receptivity mechanisms and the acoustical forcing field. This work is documented in Publication 2.1.*9* and M.S. Thesis 2.2.*4*.

In the experiment, a uniform two-dimensional roughness strip placed across the span of the plate provided a receptivity mechanism. The width of the strip was chosen to be one-half of the Tollmien-Schlichting (T-S) wavelength of interest. Acoustical forcing was applied by a speaker placed upstream of the flat-plate model. This 2-D roughness element provides the site for local adjustment in the boundary layer that is needed in order to convert the long wavelength acoustical disturbance to the short-wavelength T-S wave. The measured disturbance profile corresponded to the T-S wave amplitude and phase predicted by linear stability theory. The phase distribution and the wavelength of the disturbance also matched predicted values. The T-S waves produced in this experiment were exceptionally clean, comparable in character to T-S waves excited by a vibrating ribbon. The observed receptivity increased linearly over a range of roughness heights predicted by triple-deck theory. The departures from linearity were documented.

One of the more important observations of this experiment is the linearity of the receptivity process with respect to the height of the roughness element. The amplitude of the T-S wave produced by the 2-D roughness increases on a roughly linear basis over the range of 40 - 120 μm ($y^+ = 0.7 - 2.2$) thus confirming the theory of Kerschen. Moreover, the experiments seem to confirm Bodonyi's prediction concerning the onset of nonlinear effects.

Another important result of this experiment is the observed variation of T-S wave amplitude with frequency. Since the T-S wave can be generated for other frequencies other than $F = 55$ (at $F = 55$ the T-S wavelength is approximately twice the tape width), the tape width can be detuned in the receptivity process.

3.4. Transition Mechanisms

Publications 2.1.*1*, 2.1.*2*, 2.1.*3*, and 2.1.*7* are the result of previously supported AFOSR work that came to print during the tenure of this contract. The work concentrates on the identification of the different transition mechanisms and is highlighted by the award-winning photographs of reference 2.1.*2*. which led to the basic understanding of the subharmonic breakdown.

3.5. Stability of Flows with Periodic Curvature

Publication 2.1.*8* laid the foundation for analyzing the stability of flows with periodic curvature. We considered the Görtler instability problem in the case where the wall curvature changes sign. This situation cannot be solved as an eigenvalue problem and one must directly integrate the partial differential equations. The periodic curvature paper is now being written (see lectures 2.3.*16*).

The highlight of this work is that we have finally put to rest the Görtler-Wittig mechanism for transition. We show that periodic curvature *is not* destabilizing and that in most cases it is *stabilizing* because of the strong stabilization of convex curvature. Wavy walls or high-amplitude T-S waves, by themselves, do not lead to a Görtler instability.